CHAPTER II. STATEMENT OF THE PROBLEM

INTRODUCTION

2.1. From the time of the first discovery of the large amounts of energy released in nuclear reactions to the time of the discovery of uranium fission, the idea of atomic power or even atomic bombs was discussed off and on in scientific circles. The discovery of fission made this talk seem much less speculative, but realization of atomic power still seemed in the distant future and there was an instinctive feeling among many scientists that it might not, in fact, ever be realized. During 1939 and 1940 many public statements, some of them by responsible scientists, called attention to the enormous energy available in uranium for explosives and for controlled power, so that U-235 became a familiar byword indicating great things to come. The possible military importance of uranium fission was called to the attention of the government (see Chapter III), and in a conference with representatives of the Navy Department in March 1939 Fermi suggested the possibility of achieving a controllable reaction using slow neutrons or a reaction of an explosive character using fast neutrons. He pointed out, however, that the data then available might be insufficient for accurate predictions.

2.2. By the summer of 1940 it was possible to formulate the problem fairly clearly, although it was still far from possible to answer the various questions involved or even to decide whether a chain reaction ever could be obtained. In this chapter we shall give a statement of the problem in its entirety. For purposes of clarification we may make use of some knowledge which actually was not acquired until a later date.

THE CHAIN-REACTION PROBLEM

2.3. The principle of operation of an atomic bomb or power plant utilizing uranium fission is simple enough. If one neutron causes a fission that produces more than one new neutron, the number of fissions may increase tremendously with the release of enormous amounts of energy. It is a question of probabilities. Neutrons produced in the fission process may escape entirely from the uranium, may be captured by uranium in a process not resulting in fission, or may be captured by an impurity. Thus the question of whether a chain reaction does or does not go depends on the result of a competition among four processes:

1. escape,

2. non-fission capture by uranium,
3. non-fission capture by impurities,
4. fission capture.

If the loss of neutrons by the first three processes is less than the surplus produced by the fourth, the chain reaction occurs; otherwise it does not. Evidently any one of the first three processes may have such a high probability in a given arrangement that the extra neutrons created by fission will be insufficient to keep the reaction going. For example, should it turn out that process (2)--non-fission capture by uranium--has a much higher probability than fission capture, there would presumably be no possibility of achieving a chain reaction.

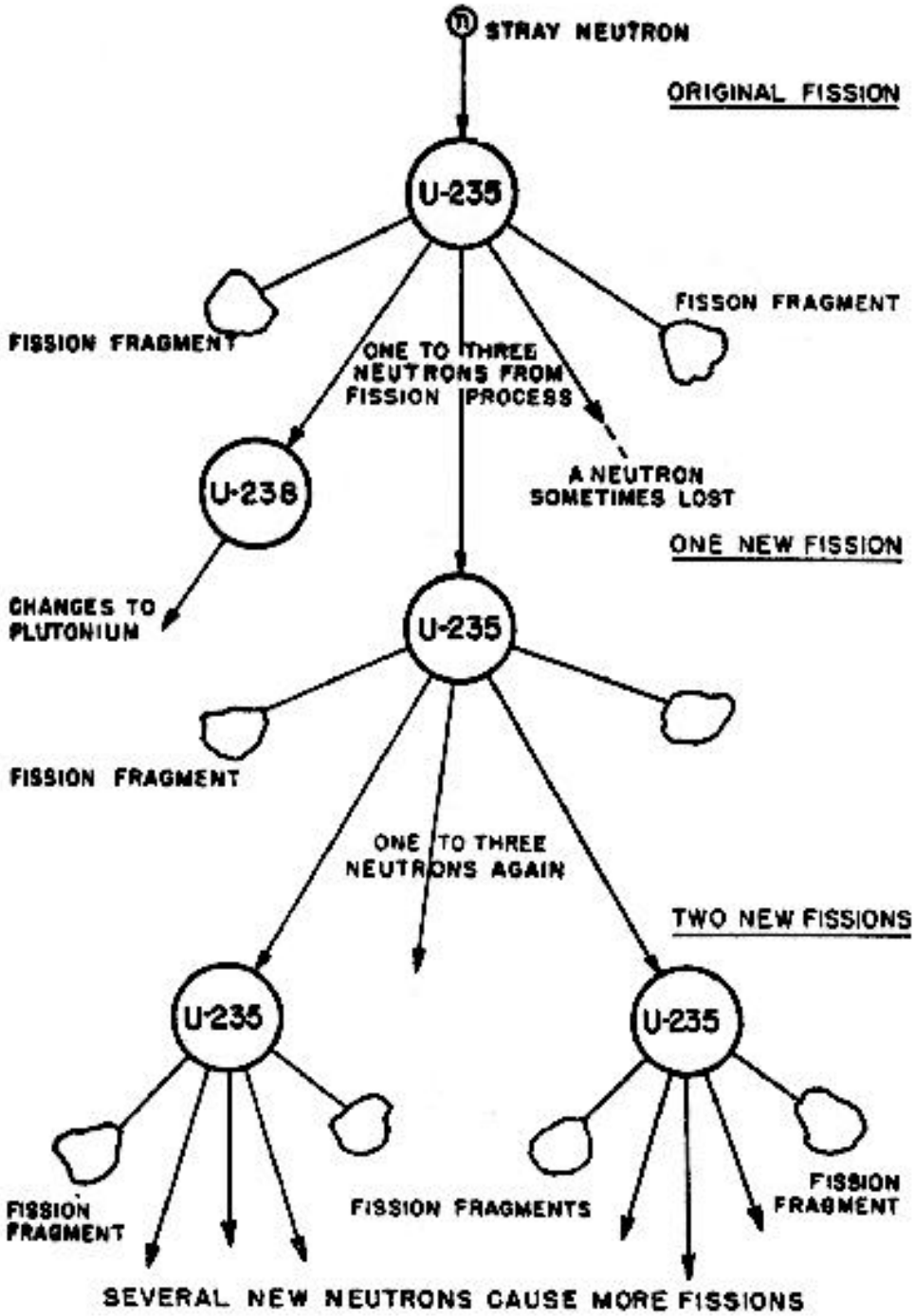
2.4. An additional complication is that natural uranium contains three isotopes: U-234, U-235, and U-238, present to the extent of approximately 0.006, 0.7, and 99.3 per cent, respectively. We have already seen that the probabilities of processes (2) and (4) are different for different isotopes. We have also seen that the probabilities are different for neutrons of different energies.

2.5. We shall now consider the limitations imposed by the first three processes and how their effects can be minimized.

NEUTRON ESCAPE; CRITICAL SIZE

2.6. The relative number of neutrons which escape from a quantity of uranium can be minimized by changing the size and shape. In a sphere any surface effect is proportional to the square of the radius, and any volume effect is proportional to the cube of the radius. Now the escape of neutrons from a quantity of uranium is a surface effect depending on the area of the surface, but fission capture occurs throughout the material and is therefore a volume effect. Consequently the greater the amount of uranium, the less probable it is that neutron escape will predominate over fission capture and prevent a chain reaction. Loss of neutrons by non-fission capture is a volume effect like neutron production by fission capture, so that increase in size makes no change in its relative importance.

2.7. The critical size of a device containing uranium is defined as the size for which the production of free neutrons by fission is just equal to their loss by escape and by non-fission capture. In other words, if the size is smaller than critical, then--by definition--no chain reaction will sustain itself. In principle it was possible in 1940 to calculate the critical size, but in practice the uncertainty of the constants involved was so great that the various estimates differed widely. It seemed not improbable that the critical size might be too large for practical purposes. Even now estimates for untried arrangements vary somewhat from time to time as new information becomes available.



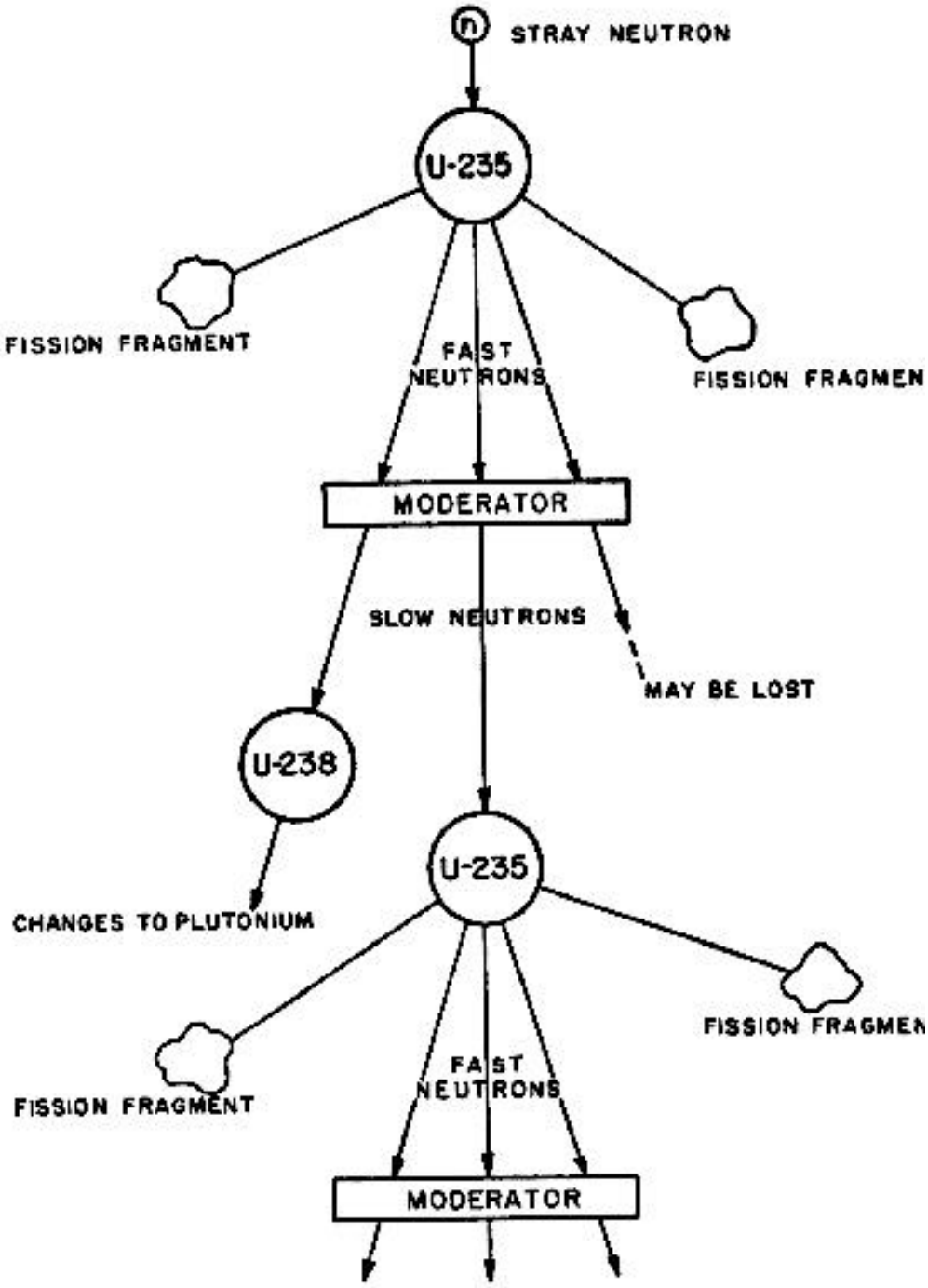
SCHEMATIC DIAGRAM OF CHAIN REACTION FROM FISSION, NEGLECTING EFFECT OF NEUTRON SPEED. IN AN EXPLOSIVE REACTION THE NUMBER OF NEUTRONS MULTIPLIES INDEFINITELY. IN A CONTROLLED REACTION THE NUMBER OF NEUTRONS BUILDS UP TO A CERTAIN LEVEL AND THEN REMAINS CONSTANT.

USE OF A MODERATOR TO REDUCE NON-FISSION CAPTURE

2.8. In Chapter I we said that thermal neutrons have the highest probability of producing fission of U-235 but we also said that the neutrons emitted in the process of fission had high speeds. Evidently it was an oversimplification to say that the chain reaction might maintain itself if more neutrons were created by fission than were absorbed. For the probability both of fission capture and of non-fission capture depends on the speed of the neutrons. Unfortunately, the speed at which non-fission capture is most probable is intermediate between the average speed of neutrons emitted in the fission process and the speed at which fission capture is most probable.

2.9. For some years before the discovery of fission, the customary way of slowing down neutrons was to cause them to pass through material of low atomic weight, such as hydrogenous material. The process of slowing down or moderation is simply one of elastic collisions between high-speed particles and particles practically at rest. The more nearly identical the masses of neutron and struck particle the greater the loss of kinetic energy by the neutron. Therefore the light elements are most effective as "moderators," i.e., slowing down agents, for neutrons.

2.10. It occurred to a number of physicists that it might be possible to mix uranium with a moderator in such a way that the high-speed fission neutrons, after being ejected from uranium and before re-encountering uranium nuclei, would have their speeds reduced below the speeds for which non-fission capture is highly probable. Evidently the characteristics of a good moderator are that it should be of low atomic weight and that it should have little or no tendency to absorb neutrons. Lithium and boron are excluded on the latter count. Helium is difficult to use because it is a gas and forms no compounds. The choice of moderator therefore lay among hydrogen, deuterium, beryllium, and carbon. Even now no one of these substances can be excluded from the list of practical possibilities. It was E. Fermi and L. Szilard who proposed the use of graphite as a moderator for a chain reaction.



SCHEMATIC DIAGRAM OF FISSION CHAIN REACTION USING A MODERATOR TO SLOW NEUTRONS TO SPEEDS MORE LIKELY TO CAUSE FISSION

USE OF A LATTICE TO REDUCE NON-FISSION CAPTURE

2.11. The general scheme of using a moderator mixed with the uranium was pretty obvious. A specific manner of using a moderator was first suggested in this country, so far as we can discover, by Fermi and Szilard. The idea was to use lumps of uranium of considerable size imbedded in a matrix of moderator material. Such a lattice can be shown to have real advantages over a homogeneous mixture. As the constants were more accurately determined, it became possible to calculate theoretically the type of lattice that would be most effective.

REDUCTION OF NON-FISSION CAPTURE BY ISOTOPE SEPARATION

2.12. In Chapter I it was stated that for neutrons of certain intermediate speeds (corresponding to energies of a few electron volts) U-238 has a large capture cross section for the production of U-239 but not for fission. There is also a considerable probability of inelastic (i.e., non-capture-producing) collisions between high-speed neutrons and U-238 nuclei. Thus the presence of the U-238 tends both to reduce the speed of the fast neutrons and to effect the capture of those of moderate speed. Although there may be some non-fission capture by U-235, it is evident that if we can separate the U-235 from the U-238 and discard the U-238, we can reduce non-fission capture and can thus promote the chain reaction. In fact, the probability of fission of U-235 by high-speed neutrons may be great enough to make the use of a moderator unnecessary once the U-238 has been removed. Unfortunately, U-235 is present in natural uranium only to the extent of about one part in 140. Also, the relatively small difference in mass between the two isotopes makes separation difficult. In fact, in 1940 no large-scale separation of isotopes had ever been achieved except for hydrogen, whose two isotopes differ in mass by a factor of two. Nevertheless, the possibility of separating U-235 was recognized early as being of the greatest importance, and such separation has, in fact, been one of the two major lines of Project effort during the past five years.

PRODUCTION AND PURIFICATION OF MATERIALS

2.13. It has been stated above that the cross section for capture of neutrons varies greatly among different materials. In some it is very high compared to the maximum fission cross section of uranium. If, then, we are to hope to achieve a chain reaction, we must reduce effect (3)--non-fission capture by impurities--to the point where it is not serious. This means very careful purification of the uranium metal and very careful purification of the moderator. Calculations show

that the maximum permissible concentrations of many impurity elements are a few parts per million--in either the uranium or the moderator. When it is recalled that up to 1940 the total amount of uranium metal produced in this country was not more than a few grams and even this was of doubtful purity, that the total amount of metallic beryllium produced in this country was not more than a few pounds, that the total amount of concentrated deuterium produced was not more than a few pounds, and that carbon had never been produced in quantity with anything like the purity required of a moderator, it is clear that the problem of producing and purifying materials was a major one.

CONTROL OF THE CHAIN REACTION

2.14. The problems that have been discussed so far have to do merely with the realization of the chain reaction. If such a reaction is going to be of use, we must be able to control it. The problem of control is different depending on whether we are interested in steady production of power or in an explosion. In general, the steady production of atomic power requires a slow-neutron-induced fission chain reaction occurring in a mixture or lattice of uranium and moderator, while an atomic bomb requires a fast-neutron-induced fission chain reaction in U-235 or Pu-239, although both slow- and fast-neutron fission may contribute in each case. It seemed likely, even in 1940, that by using neutron absorbers a power chain reaction could be controlled. It was also considered likely, though not certain, that such a chain reaction would be self-limiting by virtue of the lower probability of fission-producing capture when a higher temperature was reached. Nevertheless, there was a possibility that a chain-reacting system might get out of control, and it therefore seemed necessary to perform the chain-reaction experiment in an uninhabited location.

PRACTICAL APPLICATION OF THE CHAIN REACTION

2.15. Up to this point we have been discussing how to produce and control a nuclear chain reaction but not how to make use of it. The technological gap between producing a controlled chain reaction and using it as a large-scale power source or an explosive is comparable to the gap between the discovery of fire and the manufacture of a steam locomotive.

2.16. Although production of power has never been the principal object of this project, enough attention has been given to the matter to reveal the major difficulty: the attainment of high-temperature operation. An effective heat engine must not only develop heat but must develop heat at a high temperature. To run a chain-reacting system at a high temperature and to convert the heat generated to useful work is very much more difficult than to run a chain-reacting system at a low temperature.

2.17. Of course, the proof that a chain reaction is possible does not itself insure that nuclear energy can be effective in a bomb. To have an effective explosion it is necessary that the chain reaction build up extremely rapidly; otherwise only a small amount of the nuclear energy will be utilized before the bomb flies apart and the reaction stops. It is also necessary that no premature explosion occur. This entire "detonation" problem was and still remains one of the most difficult problems in designing a high-efficiency atomic bomb.

POSSIBILITY OF USING PLUTONIUM

2.18. So far, all our discussion has been primarily concerned with the use of uranium itself. We have already mentioned the suggestion that the element of atomic number 94 and mass 239, commonly referred to as plutonium, might be very effective. Actually, we now believe it to be of value comparable to pure U-235. We have mentioned the difficulty of separating U-235 from the more abundant isotope U-238. These two isotopes are, of course, chemically identical. But plutonium, although produced from U-238, is a different chemical element. Therefore, if a process could be worked out for converting some of the U-238 to plutonium, a *chemical* separation of the plutonium from uranium might prove more practicable than the *isotopic* separation of U-235 from U-238.

2.19. Suppose that we have set up a controllable chain reaction in a lattice of natural uranium and a moderator--say carbon, in the form of graphite. Then as the chain reaction proceeds, neutrons are emitted in the process of fission of the U-235 and many of these neutrons are absorbed by U-238. This produces U-239, each atom of which then emits a beta particle, becoming neptunium ($_{93}Np^{239}$). Neptunium, in turn, emits another beta particle, becoming plutonium **(**$_{94}Pu^{239}$**),** which emits an alpha particle, decaying again to U-235, but so slowly that in effect it is a stable element. (See figure on p. 8.) If, after the reaction has been allowed to proceed for a considerable time, the mixture of metals is removed, it may be possible to extract the plutonium by chemical methods and purify it for use in a subsequent fission chain reaction of an explosive nature.

COMBINED EFFECTS AND ENRICHED PILES

2.20. Three ways of increasing the likelihood of a chain reaction have been mentioned: use of a moderator; attainment of high purity of materials; use of special material, either U-235 or Pu. The three procedures are not mutually exclusive, and many schemes have been proposed for using small amounts of separated U-235 or Pu-239 in a lattice composed primarily of ordinary uranium or uranium oxide and of a moderator or two different moderators. Such proposed arrangements are usually called "enriched piles."

USE OF THORIUM OR PROTOACTINIUM OR OTHER MATERIAL

2.21. All our previous discussion has centered on the direct or indirect use of uranium, but it was known that both thorium and protoactinium also underwent fission when bombarded by high-speed neutrons. The great advantage of uranium, at least for preliminary work, was its susceptibility to slow neutrons. There was not very much consideration given to the other two substances. Protoactinium can be eliminated because of its scarcity in nature. Thorium is relatively plentiful but has no apparent advantage over uranium.
2.22. It is not to be forgotten that theoretically many nuclear reactions might be used to release energy. At present we see no way of initiating or controlling reactions other than those involving fission, but some such synthesis as has already been mentioned as a source of solar energy may eventually be produced in the laboratory.

AMOUNTS OF MATERIALS NEEDED

2.23. Obviously it was impossible in the summer of 1940 to make more than guesses as to what amounts of materials would be needed to produce:

1. a chain reaction with use of a moderator:
2. a chain-reaction bomb in pure, or at least enriched, U-235 or plutonium.

A figure of one to one hundred kilograms of U-235 was commonly given at this time for the critical size of a bomb. This would, of course, have to be separated from at least 140 times as much natural uranium. For a slow-neutron chain reaction using a moderator and unseparated uranium it was almost certain that tons of metal and of moderator would be required.

AVAILABILITY OF MATERIALS

2.24. Estimates of the composition of the earth's crust show uranium and thorium both present in considerable quantities (about 4 parts per million of uranium and 12 parts per million of thorium in the earth's crust). Deposits of uranium ore are known to exist in Colorado, in the Great Bear Lake region of northern Canada, in Joachimstal in Czechoslovakia, and in the Belgian Congo. Many other deposits of uranium ore are known, but their extent is in many cases unexplored. Uranium is always found with radium although in much larger quantity. Both are often found with vanadium ores. Small quantities of uranium oxide have been used for many years in the ceramics industry.
2.25. Thorium is also rather widely distributed, occurring as thorium oxide in fairly high concentration in monazite sands. Such sands are found to some extent in this country but particularly in Brazil and in British India.

2.26. Early rough estimates, which are probably optimistic, were that the nuclear energy available in known deposits of uranium was adequate to supply the total power needs of this country for 200 years (assuming utilization of U-238 as well as U-235).
2.27. As has already been mentioned, little or no uranium metal had been produced up to 1940 and information was so scant that even the melting point was not known. (For example, the *Handbook of Physics and Chemistry* for 1943-1944 says only that the melting point is below 1850 ° C. whereas we now know it to be in the neighborhood of 1150 °.) Evidently, as far as uranium was concerned, there was no insurmountable difficulty as regards obtaining raw materials or producing the metal, but there were very grave questions as to how long it would take and how much it would cost to produce the necessary quantities of pure metal.
2.28. Of the materials mentioned above as being suitable for moderators, deuterium had the most obvious advantages. It is present in ordinary hydrogen to the extent of about one part in 5,000. By 1940 a number of different methods for separating it from hydrogen had been developed, and a few liters had been produced in this country for experimental purposes. The only large-scale production had been in a Norwegian plant, from which several hundred liters of heavy water **(**D_20**,** deuterium oxide) had come. As in the case of uranium, the problem was one of cost and time.
2.29. Beryllium in the form of beryllium silicates is widely found but only in small quantities of ore. Its use as an alloying agent has become general in the last few years; for such use, however, it is not necessary to produce the beryllium in metallic form. In 1940 only 700 pounds of the metal were produced in this country.
2.30. As far as carbon was concerned, the situation was obviously quite different. There were many hundreds of tons of graphite produced every year in this country. This was one of the reasons why graphite looked very desirable as a moderator. The difficulties lay in obtaining sufficient quantities of graphite of the required purity, particularly in view of the expanding needs of war industry.

TIME AND COST ESTIMATES

2.31. Requirements of time and money depended not only on many unknown scientific and technological factors but also on policy decisions. Evidently years of time and millions of dollars might be required to achieve the ultimate objective. About all that was attempted at this time was the making of estimates as to how long it would take and how much it would cost to clarify the scientific and technological prospects. It looked as if it would not be a very great undertaking to carry along the development of the thermal-neutron chain reaction in a graphite-uranium lattice to the point of finding out whether the reaction would in fact go. Estimates made at the time were that approximately a year and $100,000 would be required to get an answer. These estimates

applied to a chain-reacting system of very low power without a cooling system or any means for using the energy released.

HEALTH HAZARDS

2.32. It had been known for a long time that radioactive materials were dangerous. They give off very penetrating radiations--gamma rays--which are much like X-rays in their physiological effects. They also give off beta and alpha rays which, although less penetrating, can still be dangerous. The amounts of radium used in hospitals and in ordinary physical measurements usually comprise but a few milligrams. The amounts of radioactive material produced by the fission of uranium in a relatively small chain-reacting system may be equivalent to hundreds or thousands of grams of radium. A chain-reacting system also gives off intense neutron radiation known to be comparable to gamma rays as regards health hazards. Quite apart from its radioactive properties, uranium is poisonous chemically. Thus, nearly all work in this field is hazardous--particularly work on chain reactions and the resulting radioactive products.

METHOD OF APPROACH TO THE PROBLEM

2.33. There were two ways of attacking the problem. One was to conduct elaborate series of accurate physical measurements on absorption cross sections of various materials for various neutron-induced processes and various neutron energies. Once such data were available, calculations as to what might be done in the way of a chain reaction could be made with fair accuracy. The other approach was the purely empirical one of mixing uranium or uranium compounds in various ways with various moderators and observing what happened. Similar extremes of method were possible in the case of the isotope-separation problem. Actually an intermediate or compromise approach was adopted in both cases.

POWER VS. BOMB

2.34. The expected military advantages of uranium bombs were far more spectacular than those of a uranium power plant. It was conceivable that a few uranium bombs might be decisive in winning the war for the side first putting them into use. Such thoughts were very much in the minds of those working in this field, but the attainment of a slow-neutron chain reaction seemed a necessary preliminary step in the development of our knowledge and became the first objective of the group interested in the problem. This also seemed an important step in convincing military authorities and the more skeptical scientists

that the whole notion was not a pipe dream. Partly for these reasons and partly because of the extreme secrecy imposed about this time, the idea of an atomic bomb does not appear much in the records between the summer of 1940 and the fall of 1941.

MILITARY USEFULNESS

2.35. If all the atoms in a kilogram of U-235 undergo fission, the energy released is equivalent to the energy released in the explosion of about 20,000 short tons of TNT. If the critical size of a bomb turns out to be practical--say, in the range of one to one hundred kilograms--and all the other problems can be solved, there remain two questions. First, how large a percentage of the fissionable nuclei can be made to undergo fission before the reaction stops; i.e., what is the efficiency of the explosion? Second, what is the effect of so concentrated a release of energy? Even if only 1 per cent of the theoretically available energy is released, the explosion will still be of a totally different order of magnitude from that produced by any previously known type of bomb. The value of such a bomb was thus a question for military experts to consider very carefully.

SUMMARY

2.36. It had been established (1) that uranium fission did occur with release of great amounts of energy; and (2) that in the process extra neutrons were set free which might start a chain reaction. It was not contrary to any known principle that such a reaction should take place and that it should have very important military application as a bomb. However, the idea was revolutionary and therefore suspect; it was certain that many technical operations of great difficulty would have to be worked out before such a bomb could be produced. Probably the only materials satisfactory for a bomb were either U-235, which would have to be separated from the 140-times more abundant isotope U-238, or Pu-239, an isotope of the hitherto unknown element plutonium, which would have to be generated by a controlled chain-reacting process itself hitherto unknown. To achieve such a controlled chain reaction it was clear that uranium metal and heavy water or beryllium or carbon might have to be produced in great quantity with high purity. Once bomb material was produced a process would have to be developed for using it safely and effectively. In some of the processes, health hazards of a new kind would be encountered.

POLICY PROBLEM

2.37. By the summer of 1940 the National Defense Research Committee had been formed and was asking many of the scientists in the country to work on various urgent military problems. Scientific personnel was limited although this was not fully realized at the time. It was, therefore, really difficult to decide at what rate work should be carried forward on an atomic bomb. The decision had to be reviewed at frequent intervals during the subsequent four years. An account of how these policy decisions were made is given in Chapters III and V.